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INVESTIGATION OF FABRIC WEAVE CONSTRUCTION VERSUS TEAR RESISTANCE

L. Howard Olson
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14 June 1977

FINAL REPORT FOR PERIOD APRIL 1976 - JUNE 1977

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The Army is currently procuring collapsible fuel tanks in the range of 3,000 to 50,000 gallons. To improve the ruggedness and durability of these tanks and to allow for development of tanks of much greater capacity, the tear resistance of substrate fabric used in tank construction must be improved. This investigation was directed at identifying those factors of weave construction which enhance fabric tear resistance, and producing and testing fabric samples to determine conditions for optimum performance. A thorough literature survey on fabric tear resistance was conducted. The literature indicated that yarn strength and yarn mobility, related to fiber strength and woven fabric geometry, directly affect fabric tear strength.

Fabrics were produced to comply with areal density and thickness given in MIL-To-52766 for the 50,000 gallon fuel storage tank. DuPont Type 715 nylon yarn of 840 denier and 1050 denier were woven into fabrics of plain, basket, and twill weave designs at 18x18 through 28x28 ends/inch x picks/inch. Considering both tear strength and dimensional stability of these fabrics, a 28x28, 2-2 basket weave fabric constructed with 1050 denier yarn gave best overall performance, yielding tear strength above 200 lbs. Tongue tear test method was used for comparative evaluation of the samples.

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PREFACE

The following is a list of suppliers for materials obtained externally during this work:

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3.) Kevlar 29 Woven Fabric

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Huguet Fabrics Division
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INVESTIGATION OF FABRIC TEAR RESISTANCE VS. WEAVE CONSTRUCTION

INTRODUCTION

The Department of the Army has been procuring coated fabric collapsible fuel storage tanks in sizes from 3000 to 50,000 gallons since the early 1960's. Because of a desire to improve the ruggedness and durability of these tanks and to allow for the development of tanks of much large capacities, the tear resistance of the coated fabric used in tank construction must be improved. Therefore, the purpose of the work was to investigate the parameters of weave construction by which uncoated fabric tear resistance may be maximized. To accomplish this objective, two major phases of the work were identified, which were: firstly, a thorough literature survey of prior research on factors affecting fabric tear resistance, and secondly, design, construction, and testing of fabrics to obtain maximum tear resistance.

The design of experimental fabrics followed guidelines established in the literature and was extended to include the most recent developments in fiber type and fabric design for applications in coated structures. Advice on fiber selection was obtained from representatives of American Enka, Monsanto and DuPont, all well-established and well-known fiber producers. External advice on the most current developments in high strength coating substrates was taken from ongoing work on the skirts and seals of large surface effect vehicles (SEV). The researchers in this area include Bell Aerospace, Goodyear Aerospace and B.F. Goodrich. Much of the work in the SEV program has not been completed or released. Thus, only segments or brief releases were available to the Georgia Tech investigators.

The work carried out under this program is specifically directed to improve tear resistance of uncoated fabrics (substrate fabrics), but

consideration was given throughout to the long term goals of the fuel tank program. This consideration is seen in several aspects of the fabric development work.

Special fabric constructions, including a fabric made with twisted filling and one with an energy barrier yarn, are included. While the first of these was not anticipated to show improved tear resistance in the uncoated form and the second was an unusual construction in terms of normal industrial practice, both were seen as having potential benefits to coated fabric tear resistance.

Attention was also given to fabric stability in that some fabric constructions with good tear resistance have low in-plane resistance to shearing. Fabrics of this type would very impractical in the coating process, where normal handling would cause numerous fabric defects. One such fabric at the low end of in-plane shear resistance is included in the experimental group of fabrics - a plain weave fabric with 18 ends/inch x 18 picks/inch construction with 840 denier nylon yarn. Furthermore, all fabric designs were selected to comply with the maximum fabric thickness of the MIL-T-52766 specification for the 50,000 gallon fuel tank, since reliable coatings and coating procedures have been established for this range of fuel tank materials.

FIRST SECTION: LITERATURE SURVEY ON FABRIC TEAR RESISTANCE

A. Introduction

The purpose of this literature survey is to identify those factors which affect resistance to tearing of fabrics. Because tearing is the most common type of failure of apparel fabrics, terminating the useful life of a garment, the literature reflects strongly a concern for the types of tear failure associated with apparel usage, i.e., snag tear failures under a steady load or sudden impulse loading. Although this type tear failure has been widely studied,[13] it is not considered relevant to above ground fuel tank failures and consequently references to snag failures are not emphasized in this study.

Studies of tear are mostly empirical and qualitative in nature rather than analytical. Thus, this study undertakes to isolate the general inferences of the studies, most of which are based upon work on light weight fabrics. The inferred points are supported by a few references on high performance fabrics such as parachutes, gliding decelerators, and surface effect vehicle skirts.

B. Abstracting Services Employed

The approach to this search was primarily through recognized abstracting services covering the textile and related engineering literature. This in turn led to the reviews and cited literature reported in individual papers. The number of citations is modest because not a great quantity of work has been written on non-snag type tearing -- particularly on the analysis of factors which affect tear resistance.

Table 1. List of Abstracting Services

Abstracting Service	Number of Years Searched	Base Support Organization	Number of Journals Reviewed by the Abstracting Service
World Textile Abstracts	1922-1976	Shirley Institute Manchester, Engl.	500
Textile Technology Digest	1944-1976	Institute of Textile Technology, Charlottesville, Va.	200
Engineering Index	1939-1976	Engineering Index, Inc.	2,400
Chemical Abstracts	1937-1974	American Chemical Society	8,000-16,000
Government Reports-Announcements and Index	1962-1976	U.S. Dept. of Commerce	Government sponsored research, development and engineering reports and other analyses prepared by Federal Agencies, their contractors and grantees.
Scientific and Technical Aerospace Reports (STAR)	1963-1976	National Aeronautics and Space Administration	Reports by NASA, NASA contractors, other government agencies and translations of foreign language works.

Table 1.(page 2) indicates the principle abstracting services used and some pertinent statistics related to these services.

In view of the coverage offered by those services, the majority of important works on tear resistance are believed to have been reviewed.

C. Standard Definitions of Tear

Tear is the sequential or spontaneous breaking of yarns in a fabric, either singly or in small groups, along a line through the fabric. Typically, the yarns being broken are transverse to the principle load direction.[30] Tear can occur as the result of a steadily increasing load or as crack propagation initiated in a prestressed fabric.

Tear by application of a steadily increasing load is described by Krook and Fox[31] in an analysis of the tongue tear test. The test specimen, as shown in Figure 1, is clamped in the jaws of a tensile testing machine. During the test, the longitudinal or load bearing set of yarns lose crimp and slip across the transverse set of yarns. The transverse yarns cross a del (Δ) shaped opening in which there are no longitudinal yarns. As the load increases, longitudinal yarns slip closer together increasing the size of the del and increasing the frictional contact and load transfer from the longitudinal set of yarns to the transverse set. The transverse yarns fail sequentially from the open edge of the del. Normally, this test is performed on a constant rate of extension tester.

In contrast to this type of tear failure, the phenomenon of crack propagation has also been studied and discussed.[4,5,22] This type of tear failure usually occurs when the fabric is under a high uniaxial or multiaxial stress such that individual yarns are at a significant proportion of their ultimate tensile strength. A crack (cut or rip) introduced in the fabric while under load produces a tear which appears to propagate spontaneously across the fabric.

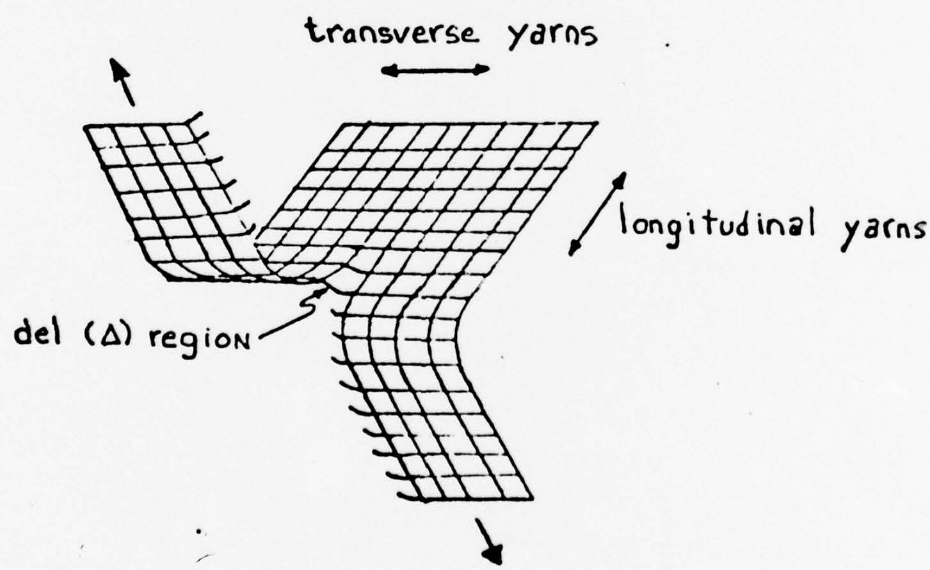

Figure 1. Tongue Tear Test Specimen

D. Factors Affecting Tear Strength

1) Type of Yarn

a) Single End Strength

Many authors* agreed that during tearing yarns are usually broken singly or in groups and that tear strength is at least roughly proportional to the single end (individual yarn) strength of the yarns broken, if other factors remain unaltered. Discussion of crack propagation type failure[5] related tear strength to yarn strength, as yarn strength directly influences fabric tensile strength, i.e., tear strengths were found to range from 30% to 90% of fabric tensile strength with other factors, such as weave construction, having significant influence.

b) Yarn Extensibility

An increase in tear strength was generally found to accompany an increase in yarn elongation.[23,24,26,27,50,54] In tongue type tears, greater elongation permits a larger del and thus more load sharing between the leading yarn in the del and its neighbors. This load sharing allows the fabric to offer greater resistance to tear propagation. Steele and Gruntfest[50], using the trapezoid tear test method, found a linear relationship between tear strength and a function of yarn rupture elongation. If E represents the yarn rupture elongation, the function has the form $[(1.0 + E) \ln (1.0 + E)] - E$.

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*See references: 13,14,26,27,31,34,47,48,53,58.

Gagliardi and Nussele[24] developed the following relation for trapezoidal tear strength:

$$T = \frac{m\,P\,E}{2} + b,$$

where

T = fabric trapezoidal tear strength

P = fabric tensile strength (ravelled strip)

E = % fabric rupture elongation

m = slope factor relating fabric toughness to tear resistance

b = constant dependent on the fabric construction

This finding was supported by Hager, et al.[26]

In further studies by Gagliardi and Gruntfest[23], certain fabrics were treated with crease-proofing agents which reduced yarn extensibility with little effect on yarn tensile strength, i.e. the yarn modulus was increased. They found that this decreased fiber capacity for energy absorption and also the ability of the yarns and fabrics to distribute those stresses applied in tearing gave lowered tear resistance.

c) Yarn Twist

Several observations were noted in reports on the effect of yarn twist. A paper by Teixira, et al[54] plotted yarn twist versus normalized tear force, defined as fabric tear strength divided by individual yarn breaking strength. Staple fiber yarns were used. In almost all cases, tear strength increased up to an optimum yarn twist value, then fell at higher twist levels. In fabrics made of continuous filament yarns, tear resistance decreased steadily as twist increased.

Abbott[2] and Foster[20] agreed that in order to produce a light weight coated fabric with high tearing strength, continuous filament yarns with low twist should be used. On the other hand, Fisher[19] observed that the tear strength of coated fabrics increases as yarn twist is increased because the degree of penetration of the primer compound into the yarns decreases significantly with increasing twist. This reduces the restriction of fiber mobility and thereby enhances tear resistance.

In a discussion by Taylor[53], the following clarifying points were brought out:

1) The single-end strength of staple fiber yarns increases as twist factor increases until an optimum twist level is reached. Thereafter, strength falls as twist increases. (The single end strength of continuous filament yarns decreases steadily as twist increases).

2) An increase in twist factor tends to make yarns more compact, thus reducing their diameter and increasing the space between threads. This can increase yarn mobility which favors an increase in tear strength.

The observations on coated fabric fiber mobility (and yarn mobility) are supported by data gathered for design of surface effect vehicle skirts,[7] in which the increased freedom of movement of higher twist yarns led to tear strength improvement. These skirts are heavy weight fabrics similar to fuel tank fabrics.

d) Yarn Smoothness or Roughness

Generally, the smoother a yarn is, the greater is the ability to have interyarn slippage -- and thus the greater the fabric tear strength.

O'Brien and Weiner[39] compared the tear strengths of fabrics made of mercerized and unmercerized cotton yarns. The mercerized yarn had a smoother, glossier surface. Results showed that fabrics made with mercerized yarn had consistently higher tear strength. Lower frictional forces existed between the mercerized yarns which allowed easier fabric distortion. In addition, tests with combed cotton yarn and carded cotton yarn showed that fabrics made of combed yarns, which are smoother than carded yarns, gave higher tear strength.

II) Type of Fabric

a) Yarn Spacing (fabric construction)

Fabric construction was generally seen to be a most important factor in determining the tear strength of fabrics.* Fabric construction is defined as the yarn frequency in yarns per unit length across the warp and filling yarn directions. The number of warp yarns per inch (ends/in.) and filling yarns per inch (picks/in.) are normally controlled fabric specifications. Yarn spacing or period is the reciprocal of yarn frequency as given in fabric construction specifications and yarn spacing directly affects yarn mobility and ease of slippage.

Krook and Fox[31], using fabrics whose construction ranged from 50 to 160 yarns per inch, showed that tear strength increases as the number of yarns per inch decreases -- specifically as the number of yarns per inch in the transverse direction decreases. In a study conducted by Devorakonda and Pope[14], the tear efficiency factor (ratio of fabric tear strength to yarn single end strength) was measured against the ratio of ends per inch to picks per inch, where the picks or filling

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*See references: 27,31,13,47,34,14,53,26,39,11

yarns were always the transverse yarns during tear testing. Using twill weave fabrics and the tongue tear test method, a straight line relation was obtained, i.e., as the ratio of ends to picks per inch increased, the tear efficiency factor increased.

In contrast to this, Teixira, et al.[54] found for a range of plain weave fabrics that the number of yarns/inch did not produce significant differences in tear, particularly when compared to the effect of other weaves. Similar findings were observed by Scheifer, et al.[45] This has been partially attributed to the fact that the plain weave has the greatest yarn interlacing density and thus has the highest inter-yarn resistance to slippage. As a result, the number of yarns under tension in the del area is relatively unaffected by yarn spacing.

b) Weave Design

Weave design influences tear strength primarily by control of the relative frequency of yarn interlacing or crossover points. It affects the sleaziness of a fabric, i.e., the ease of thread slippage and the number of threads woven together and thus breaking together. Many researchers have found a basket weave very suitable for producing optimum tear resistant fabrics.*

As stated by Teixira, et al.[54], a weave with many crossovers/inch, i.e., a plain weave, has greater gripping action between warp and filling threads and, thus, increased resistance to yarn slippage and mobility which

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*See references: 27,31,13,47,5,22,54,7,2,3,41,44,11

in turn decreases fabric tear strength. A weave with long floats will allow greater distortion and will thus have a greater resistance to tearing. However, this results in instability and consequently may affect fabric utilization. For example, the coating of fabrics requires a certain minimal level of dimensional stability, and tear strength is optimized rather than maximized by the proper choice of weave design and yarn spacing.

Experimental studies by the authors cited above showed a 2/2 basket weave to have about twice the tear strength of a plain weave, and a 3/1 twill weave to have about 1.5 times the tear strength of a plain weave. Abbott[13] made the following remark on weave design of coated fabrics:

> "Basket weaves are less tightly woven than plain weaves at the same cover factor (that is the same number of ends and picks per inch of the same yarn). As a result, they tend to be more completely penetrated by coating, and their tearing strength is reduced much more than is that of a tightly woven plain weave. Thus, although in the uncoated state a basket weave may have a tearing strength which is perhaps four times that of a plain weave of the same cover factor, in the coated state the tearing strengths may not be very different."

(Further comments on effects of coatings appear later.)

A series of tests[11] on coated heavy weight polyester fabrics gave the following ranking in terms of tear strength:

1) 3 - 4 basket

2) 2 - 2 basket

3) 2/2 twill

4) 4 harness satin

5) plain weave

Obviously, weave design influences tear strength, but it is difficult to conclude from the literature that one particular weave is best since trade-offs between ease of manufacture, stability, etc. and tear strength are necessary, and are reflected in the fabrics chosen for test in the literature. The general trend is that the longer the yarn float the better the fabric will perform in tear. Also, yarn grouping (2-2 basket vs. 2-2 twill) enhance resistance to tear.

c) Crimp Level (due to interlacing)

Harrison[27] in a literature review on fabric tear strength stated that crimp could act in two ways:

i) a higher crimp level will lead to a more extensible fabric which allows wider distribution of stresses around the point of tearing.

ii) on the other hand, higher crimp also leads to a reduction of slippage because of the greater extent of yarn wrap, i.e., one yarn bending around another, and interlacing.

O'Brien and Weiner[39] defined crimp balance as C_1/C_2, where C_1 and C_2 are warp and filling crimp levels. Crimp level, C, may be defined as $(L_1 - L_2)/L_1$, where L_1 is the total length of yarn in a weave repeating unit and L_2 is the length of the weave repeating unit or end to end distance of the yarn after being woven into a fabric weave repeating unit. The closer the value of C_1/C_2 is to 1.0, the higher the tear strength of the fabric. Abbott recommended that crimp be held to a minimum in order that translation of fiber strength to fabric tear strength be maximized.

d) Multiple Fabric Layers

Huebner[29] observed that the rip strength of two fabric layers when not connected to one another was approximately twice the single fabric strength as one might expect. A 20% reduction in rip strength occurred when the fabrics were bonded together with a starch solution. Steele and Gruntfest[50] used single, double and triple fabric layers in trapezoid tear tests without bonding and found a linear increase in tear strength with the number of layers.

e) Fabric Reinforcement

Reinforced fabrics contain periodically spaced yarns that are intended to increase tensile and tear strengths. The reinforcement may be contained in the fabric structure as single high strength yarns (or yarn bundles) alternately, as a component of a yarn.[35]

Freeston and Claus[22] agree with Abbott and Skelton[5] in stating that the best method of blocking crack propagation in a fabric is to

use energy barrier yarns. These are individual yarns with very high strength woven periodically in both warp and filling directions or a weave design that enables groups of yarns woven periodically in both the warp and filling direction to act together.

A fabric patented by Kaltenback[1] used this principle in the form of 2-2 basket weave ribbons attached to a plain fabric. The claims included rip-stop properties and 50% to 100% higher tear strength.

III) Effects of Fabric Finish

a) Lubrication

Freeston and Claus[22] observed a dependence of the resistance to crack propagation upon the stiffness of a fabric in shear. Lower shear stiffness generally accompanied higher resistance to crack propagation. Shear stiffness may be lowered by applying a lubricant. Steele[48] studied the effects of quaternaries of ammonium compounds which were used as fabric softeners for fabrics containing cellulosic yarns. Trapezoid, Elmendorf, and tongue tear test methods were used to evaluate fabric tear resistance with varying degrees of softener treatment. Test results showed the tongue tear test to be most sensitive to the treatment, and that tear strength increased as the concentration of the softener increased.

Scott[46] in a similar study found tear strength could be increased from 11% to 40% by the addition of softeners. Nuessle, et al.[37,38] in further work on softener additives pointed out that the increase in tear strength is the result of allowing the yarns to slide into closer contact, thus reinforcing one another.

A U.S. patent[12] has a claim of higher tear strength resulting from yarn surface treatment with oxidized high density polyethylene.

b) Crease-resistance Treatments

Crease-resistance treatments generally tend to reduce tearing strength. The additives make the fibers less extensible, stiffer and less mobile. Also, inter-yarn friction is increased. All reports in the literature indicate a decreasing trend in tear resistance as the additive concentration is increased. Post-treatment of the fabrics with softeners could improve tear performance somewhat.*

c) Coatings

In general, coatings tend to reduce fabric tear strength because the ease of yarn movement is restricted.** Fisher[19] compared the use of high and low modulus primer compounds. He found that the high modulus compound resulted in 40%-60% decrease in tear strength, while the low modulus primer resulted in only 20% decrease in tear strength. Abbott and Lannefeld[2] agreed with the findings, with the additional point that polyurethanes were found to be most attractive as a soft base since the compound did not fully penetrate the fabric structure. Abbott[1] found that the lower modulus primer coat still improved tear strength although stiffer top coats were added above the primer.

Painter and Frisolli obtained a patent[40] on the concept of fabric pretreatment with a softener prior to coating. The claim stated that tear strength could be doubled by the pretreatment.

d) Heat Setting

Heat setting appears to indirectly effect tear strength. If lubricating oils are driven off, the fabric will be weaker in tear as

* References: 27,55,48,49,5,38,37,24

**References: 27,22,7,4,3,1,19,20,40,39

has been discussed previously. Heat shrinkage tends to decrease fabric openness and decrease tear strength. Post-treatment of fabrics with lubricants after heat setting improves tear resistance.[6]

IV. Effects of Tear Test Procedure

a) Speed of Tear Propagation

Sarma[17,18] and Abbott and Skelton[14] (working with coated fabrics) concluded that, as a general rule, the more rapid the tear test extension rate, the lower the tear strength. The assumption is that high tearing speed restricts the ability of mobile yarns to achieve the optimum configuration for stress distribution or load sharing.

b) Gauge Length

Steel and Gruntfest[2] studied the effect of gauge length on the trapezoidal test tear strength of very open cheesecloth structures made of cotton and rayon yarns. With the cotton structures, an increase in gauge length resulted in an increase in tear strength. The rayon structure showed no effect of gauge length upon tear strength.

c) Test Method

In comparing measured tear strengths, the test method chosen produces the most significant difference in recorded tear strength. A number of references support this point and attempt to explain and compare the results from the various test methods.* Table 2 summarizes test methods found during this literature survey. The wide variety of

*See references: 50,55,13,57,58,33,49,30,15,35,36,56

Table 2. Summary of Tear Test Methods

Tear Test Name	Source	Method of Applying Load
1.) Elmendorf Tear Test	ASTM-D-1424 ref. (41)	Falling Pendulum
2.) Pendulum Method	Fed. Std. 191 Method 5132 ref. (44)	Falling Pendulum
3.) Tongue Tear (single rip)	ASTM-D-2261 ref. (42)	Tensile - constant rate of extension
4.) Tongue Tear (single rip)	Fed. Std. 191 Method 5134 ref. (45)	Tensile - constant rate of extension
5.) Wing-rip Tear	ref. (40)	Tensile - constant rate of extension
6.) Tongue Tear (double rip)	ref. (1)	Tensile - constant rate of extension
7.) Trapezoidal Tear	ASTM-D-2263 ref. (43)	Tensile - constant rate of extension
8.) Wounded Tensile Tear	ref. (1)	Tensile - constant rate of extension
9.) Trapezoidal Tear	Fed. Std. 191 Method 5136 ref. (46)	Tensile - constant rate of extension
10.) Wounded Bursting Test	ref. (1), (30)	Diaphram - hydrodynamically loaded
11.) Snatch Tear	ref. (19), (21)	Impact - falling weight
12.) Finch Tear Resistance	U.S. Army Spec. 6-269 and Chem. Warfare Drawing No. E18-56-1 ref. (3)	Tensile - constant rate of extension
13.) Ballistic Snag Tear	ref. (5)	Falling Pendulum
14.) Impact Tear (Similar to tongue tear)	ref. (4)	Falling Pendulum
15.) W. Wegener's Method (counter-rotating pulleys)	ref. (30)	Tensile - constant rate of traverse
16.) Peg Tear Test (peg rupture and snag tear)	ref. (61)	Tensile - constant rate of traverse

test methods suggests the difficulty encountered in attempting to reproduce tear conditions simulating fabric end-use conditions. Variance in geometry and failure mechanisms lead to the disparity in test results.

Examples from the comparisons of test methods follow.

Turl[56] in a comparative study of the trapezoidal and tongue tear test results found no correlation between the data gathered by the two methods. However, the values obtained from the trapezoidal tear test were consistently higher than those from the tongue tear test. Statistically, the trapezoidal tear test method was considered much less satisfactory than the tongue tear method. Kormos[30] agreed with this conclusion because he found that the trapezoidal test had much greater variability from specimen to specimen within the same test lot.

A study of double rip tongue tear versus single rip tongue tear[57] indicated some reduction in specimen to specimen variability while retaining excellent correlation (2:1) in comparison of the two test methods.

Turl[58] in comparing the wing rip and tongue tear tests concluded that both methods measured the same property and were easily correlated with one another. The wing rip test appeared less prone to complicating problems such as thread pull-out. Ewing[15] added that the wing rip method was particularly suited for fabrics with markedly differing warp and filling yarn properties or construction. The phenomenon of change of tear direction from across warp to across filling, for example, is not as pronounced.

Kukin and Fedorova[32,33] explained the lack of cross-correlation between certain test methods by noting which set of yarns was being

torn by the applied force. Those tests which tear the set of yarns at right angles to the applied force include tongue tear, Elmendorf, wing tear and peg or spike tear test. Those tearing yarns along the direction of applied load include the trapezoidal tear, wounded tensile tear, and Wegener method. The yarns in the wounded bursting test are under multiaxial loading; and, thus, the method constitutes a third type of tear.

Steele[48,49] compared the effect of softeners on results obtained from six test methods: single rip tongue tear, double rip tongue tear, wing rip tear, pin tear, Elmendorf, and trapezoidal tear tests. The data indicated the single rip tongue tear to be most sensitive to softeners while the Elmendorf, wing rip and trapezoidal tests were little affected by the addition of softeners.

Truslow[55] concluded in tests of crease resistant fabrics that the double rip tongue tear produced more reliable results by reducing distortion during the test.

Creswick[13] with minor criticism by Millard[36] could find no reason in a comparison of six test methods to recommend one test method in preference to the others.

During the literature survey, the most commonly recurring test methods were the single rip tongue tear (also known as the "tongue tear") and the Elmendorf tear tests. In general, these two tests are widely utilized in textile industry testing laboratories.

E. Summary

The general conclusions found in the literature survey relative to fabric tear resistance are:

1) Yarn and fabric construction parameters and finishes which enhance yarn mobility increase fabric resistance to tearing. In general fabric tearing strength increases with

a) Increasing yarn denier

b) Increasing yarn twist up to some optimum value and then tearing strength decreases with further increases in twist. The optimum twist level is lower for continuous filament than for staple yarns

c) Decreasing pick and end count

d) Increasing weave float length

2) Yarn strength - Fabric tearing strength increases in direct proportion with increasing yarn strength.

and 3) Periodic incorporation of energy barriers yarn systems, e.g., yarn bundles which occur intentionally in rip-stop fabrics or by slippage in weaves such as the 2-2 basket weave.

4) Fabric coating masks the advantages of several fabric construction and weave parameters, but tear strength does tend to increase when some twist is given the yarns (increasing fabric openness).

5) Coated fabrics also appear to exhibit greater tear resistance when a low modulus primer is applied (increasing yarn mobility)

No general conclusion can be made with respect to selecting a preferred tear test method beyond noting the general acceptance of the tongue tear and Elmendorf test methods, but the test method should simulate end use as closely as possible. For example, the fuel tank fabric should be subjected to a tear test using biaxial rather than uniaxial loading.

SECOND SECTION: DESIGN, CONSTRUCTION, AND TESTING OF EXPERIMENTAL FABRICS

A. Yarn Selection

Concurring advice was received from representatives of three fiber producers - American Enka, DuPont, and Monsanto - that of the available tire cord quality nylon yarns the DuPont Type 715 nylon would be most suitable to the needs of this program. The reasons for this include low shrinkage at elevated temperature and uniformity of fiber diameter and strength along the length of the yarn. These factors are important to the coatability and tear resistance of the fabric.

This fiber is a type 6-6 nylon, a polyamide fiber, and is the strongest of the ordinary nylons currently being manufactured. The literature survey indicated that tear resistance increased as fiber strength increased, an important factor in making this selection. Also, substantial successful industrial experience with the Type 715 nylon in substrates for coating applications also was a factor in selecting this fiber for the program. Both 840 and 1050 denier standard commercial yarns were obtained.

DuPont Kevlar 29, a polyaramid fiber, was also selected for the program. Kevlar is a relatively new fiber and is thus supported by much less industrial experience than the Type 715 nylon. Nevertheless, Kevlar 29 is about 2½ times stronger and is obviously a candidate for incorporation in fuel tank designs in the near future. The abrasion resistance of Kevlar is known to be lower than nylon. A 1500 denier standard commercial yarn was obtained.

Table 3 summarizes properties of Type 715 nylon and Kevlar 29.

Table 3. Properties of Type 715 nylon and Kevlar 29

Property	Type 715 Nylon	Kevlar 29
Tenacity	8.5 - 8.8 grams/denier	22 grams/denier
Elongation	20% - 22%	3 - 4%
Boil Shrinkage	6.7%	0%
Density	1.14 grams/c.c.	1.44 grams/c.c.
Knot Strength	86%	37%

B. Fabric Design

In addition to the yarns to be incorporated into experimental fabrics, fabric design contains the additional two parameters, fabric weave and density of yarns, which are defined below.

Fabric weave is the method of interlacing the two primary sets of yarns, warp - the set parallel to the fabric length direction, and filling - the set perpendicular to the warp. The fabric weaves selected for this program are listed in Table 4 with illustrations of each weave. Each illustration is a basic repeating unit of the weave with the interlacing pattern denoted by having a filled in or dark square representing warp yarn over filling yarn and an empty or unmarked square representing filling yarn over warp yarn.

Weaves with two orthogonal sets of yarns are termed (traditional) biaxial weaves. Additionally, a proprietary process exists for producing a triaxially woven fabric*. The triaxial plain weave fabric is illustrated

* N.F. Doweave, Inc., 600 Allendale Road, King of Prussia, PA 19406

in Figure 2. The reason for adding triaxial fabrics to the program is suggested in Figure 2, in that if one set of yarns fail, a coherent pair remain to support the fabric. Triaxial fabrics represent a new technology in woven fabric production.

Table 4. Weave Constructions

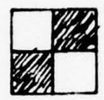
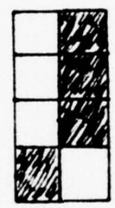
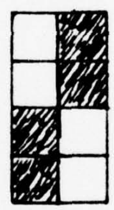
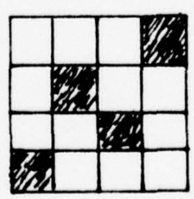
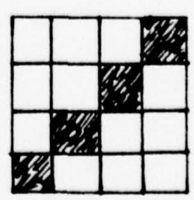
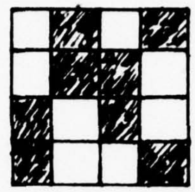
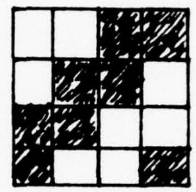
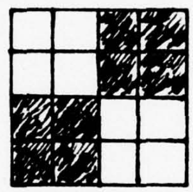
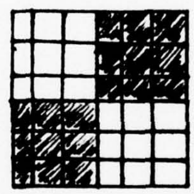
Weave Constructions	Illustration
1.) Plain Weave	
2.) 1-3 Warp Rib	
3.) 2-2 Warp Rib	
4.) 2-2 Filling Rib	
5.) 1/3 Broken Twill (4 Harness Satin)	
6.) 1/3 Regular Twill	

Table 4 (continued)

Weave Construction	Illustration
7.) 2/2 Broken Twill	
8.) 2/2 Regular Twill	
9.) 2-2 Basket	
10.) 3-3 Basket	

The triaxial weaves obtained include a plain weave, a 2-2-2 basket weave, and a bi-plane plain weave - a design in which one plain weave is woven above another and the two are linked regularly by interconnecting yarns.

A yarn passing over two or more yarns without interlacing is termed a float. The literature survey indicated that tear resistance of fabrics increased with increasing float length and less stable fabrics are more difficult to provess in coating. The reason for investigating the variety of fabric weaves shown in Table 4 was to have floats occuring in a variety of configurations which could enhance tear resistance while retaining fabric stability.

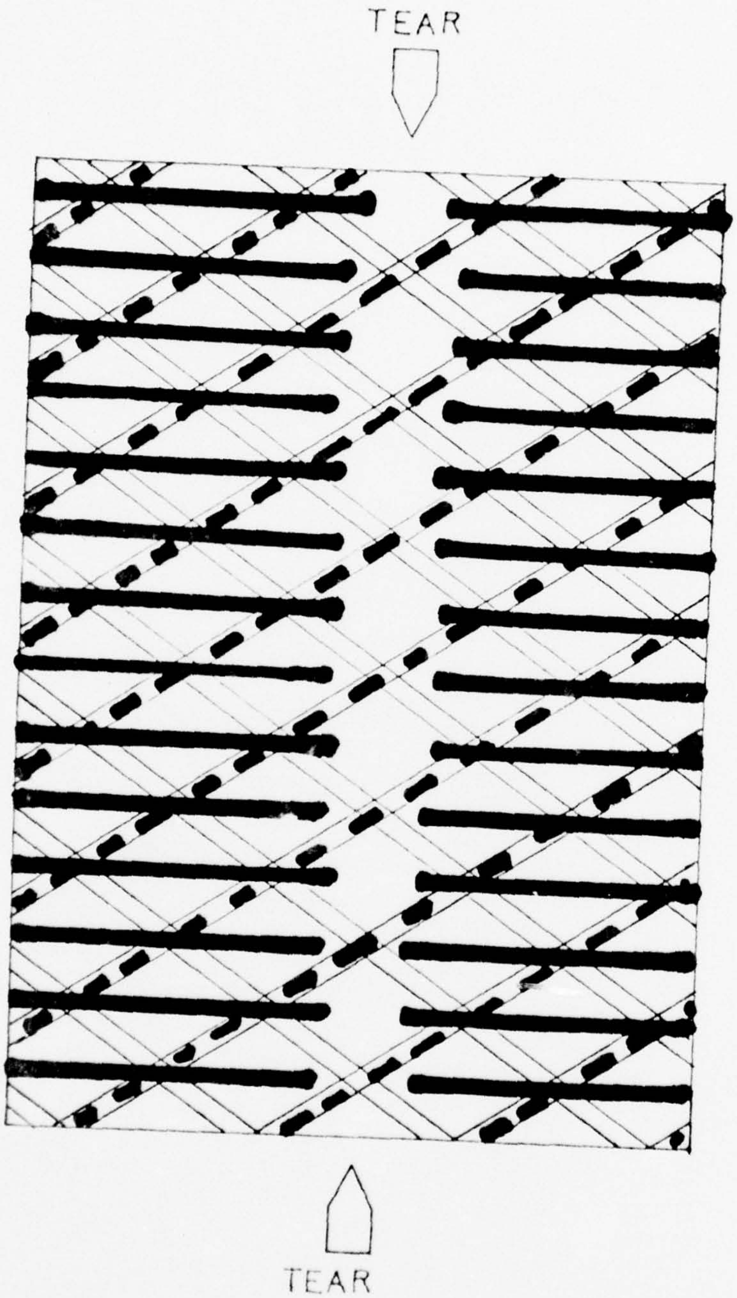


Figure 2. Triaxial Fabric

The term density of yarns is used here to mean the number of warp ends per inch and the number of filling picks per inch. The effect of increasing ends per inch or picks per inch was reported in the literature to be a decrease in tear resistance. Logically, decreasing the number of ends and picks per inch to a low level would also decrease dimensional stability (as results reported later show). Thus, the objective of varying this parameter was to find the optimum density of yarns. Since fabric properties should be uniform in both warp and filling directions, the experimental fabrics were produced with an equal number of ends per inch and picks per inch. The values selected were 18x18, 22x22, 24x24, and 28x28.

Triaxial woven fabrics were available in 18x18x18 construction for the plain weave, 9x9x9 with two yarns drawn as one in the basket weave, and 37x37x27 in the bi-plane plain weave. All are made with 840 denier nylon yarn, the bi-plane fabric contains Monsanto Type A07 yarn and the other two contain a discontinued Enka nylon. Despite the difficulty in comparing these triaxial fabrics to the biaxial weaves with the yarn source differing, these fabrics were accepted as being the best available to this program within the limitations imposed by time and cost.

C. Experimental Plan for Fabric Selection

To produce all the fabrics in all combinations outlined above (2 yarn sizes x 10 weaves x 4 end and pick counts = 80 fabrics) was beyond the scope of this program. Thus, the plan to isolate a fabric configuration of optimum tear resistance and fabric stability was to first compare and

and pick counts (density of yarns) while holding yarn denier and fabric weave constant. Then, fabric weave was varied while yarn denier, and end and pick count were held constant. Finally, the yarn denier was varied with end and pick count set to the optimum value found in the preceeding work, but corrected for equivalent cover factor based upon the change in yarn diameter. The fabric weaves of this series were selected from the optimum weaves determined previously.

A plain weave fabric was produced in each configuration as the basic reference point for comparison of the other variables. The 840 denier yarn was used in the investigation of fabric weave and end and pick count. Table 5 shows the fabrics produced under this plan.

In addition to these, a Kevlar plain woven fabric was obtained constructed with 24 ends per inch x 24 picks per inch using 1500 denier Kevlar yarn.

A sample of the 1050 denier nylon, 24x24, 2-2 basket weave fabric was produced with the filling yarn having between twisted. The reason for adding the fabric with twisted filling was that a report received on the SEV program indicated that having two to three turns per inch twist in the substrate fabric yarns resulted in improved coated fabric tear resistance over the coated fabric tear resistance obtained with untwisted yarns. However, this was not true for the uncoated fabric. In all, nineteen fabrics were produced and four purchased for evaluation. Table 6 lists the special fabric constructions not shown in Table 5.

Table 5. Plan for Fabric Selection

Weave / End & Pick Count	Plain	1-3 Warp Rib	2-2 Warp Rib	2-2 Filling Rib	1/3 Broken Twill	1/3 Regular Twill	2/2 Broken Twill	2/2 Regular Twill	2-2 Basket	3-3 Basket
18 x 18	X									
22 x 22	X									
24 x 24	X*				X**		X	X**	X**	X**
28 x 28	X	X	X	X	X	X	X	X	X	

* This fabric produced with both 840 denier and 1050 denier yarns

** This fabric produced with 1050 denier yarn only

Table 6. Special Fabric Constructions

1.) Triaxial Fabrics *

a.) 18 x 18 x 18 Plain Triaxial

b.) 9 x 9 x 9 Basket Weave Triaxial

(Two ends woven as one to be equipment in weight to the 18 x 18 x 18)

c.) 37 x 37 x 27 Bi-Plane Triaxial

(A special formation in which two fabrics nearly equivalent to the 18 x 18 x 18 are interwoven)

2.) Plain Weave (Biaxial) with 1500 Denier Kevlar Yarn

3.) 2-2 Basket Weave, 24x24, 1050 Denier Nylon Yarn
(Filling yarnw were twisted 3 turns/inch)

* Note: Fabric weave designations are assigned by N. F. Doweave, Inc., 600 allendale Road, King of Prussia, PA., 194066.

D. Fabric Construction

The preparation of filling yarns, insertion of twist for the one fabric requiring twisted filling, and weaving of experimental fabrics was done with standard industrial equipment shown in Table 7. Warp preparation, due to time and cost restrictions, was done with a sectioned beam technique assembled at Georgia Tech for projects such as this one. The sectioned beam method of warping offers the advantage of being able to produce a warp beam from relatively few packages of yarn. The components of the system are designed to handle synthetic yarns with minimal damage.

Table 7. Equipment Used in Fabric Construction

1.)	Crompton and Knowles Model C-2 loom (set up for nylon) with multiple harness dobby head. Fabrics were woven on four harness patterns with a two harness selvedge.
2.)	Roberts Arrow TM-2 Twister with traveller weight and size experimentally determined for optimum performance with the 1050 denier yarn.
3.)	Whitin-Schweiter Model MS Quiller, set up for nylon yarns.

E. Fabric Testing

A series of physical tests was performed on the experimental fabrics. These tests are recognized standard tests found in Federal Test Method 191. The tests performed are shown in Table 8.

Table 8. Fabric Physical Tests

Property	Test Method of Fed. Std. 191
Tensile Strength (1" ravelled strip)	5104
Tear Strength (Tongue)	5134
Weight	5041
Thickness	5030.2
Air Permeability	5450

The tongue tear test was modified to prevent slippage of yarns in consideration of the end use of the fabric as a coating substrate. Figure 3 illustrates the specimen configuration. Note that this specimen has a three inch free or uncoated width as is specified in Method 5134.

Special rubber faced jaws were used in the tensile tester for all tests. Few jaw breaks or slips were observed in the tests, except filling directed tensile strength tests of the Kevlar fabric. One technician experienced in these particular tests performed all the tests to reduce operator variance to the lowest possible level.

As a special test, two each of specimens of fabrics of 2/2 twill, 24x24, with 1050 denier yarn were hand stitched with Kevlar yarn in a 2-2 floating repeat on one inch centers in one fabric pair and one half

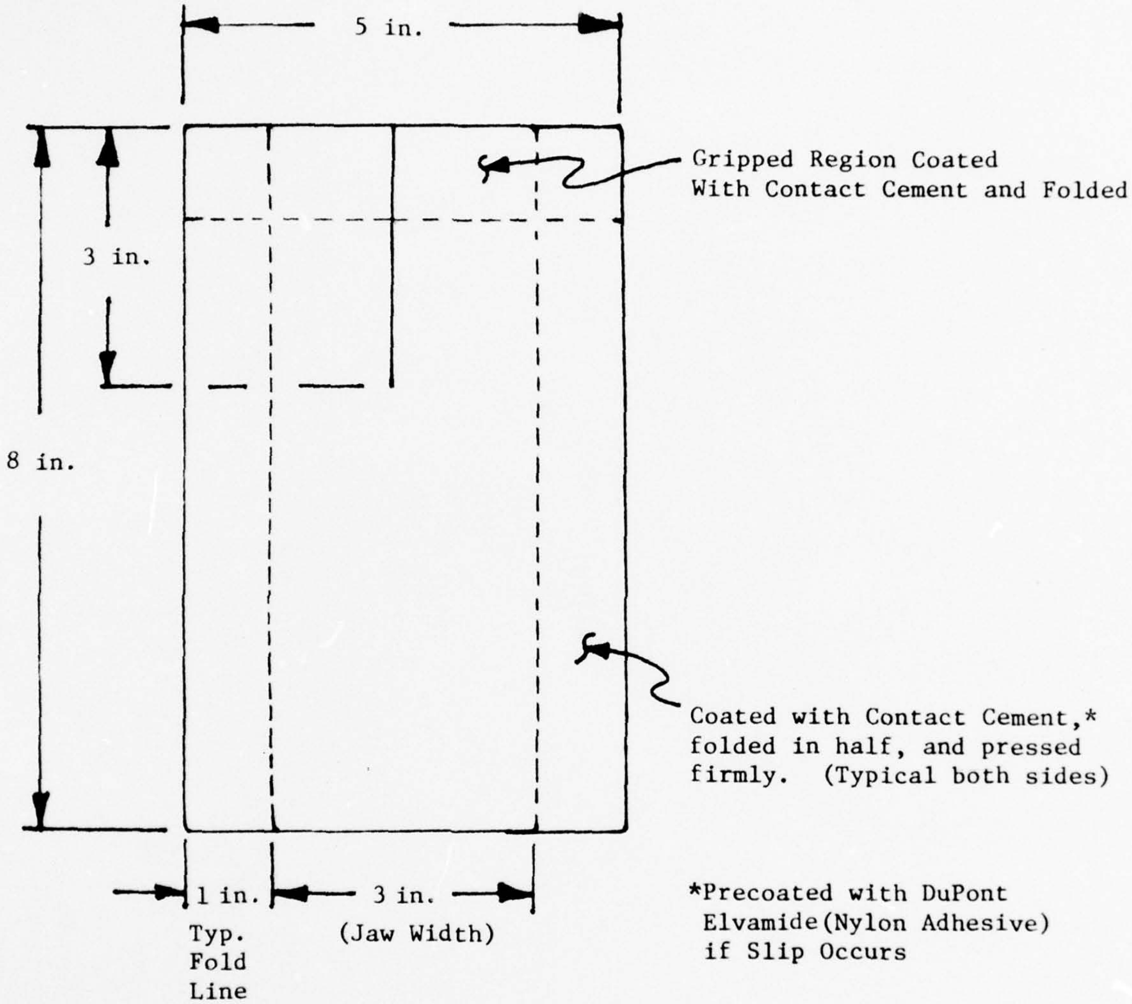


Figure 3. Tongue Tear Specimen

inch centers in another fabric pair to determine if the presence of an energy barrier yarn would produce noticeable effect on tear resistance. While this type construction would require considerable initial engineering effort to weave effectively in a production environment this technique provided the opportunity for first order evaluation of potential benefits to overall tear resistance.

F. Summary of Results

The following are summaries of results on the three series of fabrics: The first series of fabrics is constructed with 840 denier yarn. The purpose of this series was to identify optimum end and pick count and weave design considering tear resistance and suitability of the fabric for the coating process in terms of fabric dimensional stability. Some weave designs give unbalanced results in that a significant margin exists between warp and filling directed tear tests. These fabrics are not suitable for the fuel tank program unless future work shows that uniform difference in skin loading occurs between the lengthwise and widthwise directions of the tank. The weaves which exhibited balanced tear properties (± 5%) include the plain weave, 1/3 twill (regular or broken), 2/2 twill (regular or broken in 28x28 construction) and 2-2 basket.

The 18x18 and 22x22 fabric constructions were extremely loose, and therefore subject to yarn slippage and geometric shear despite "laboratory conditions", making them unsuitable for the fuel tank program. The 28x28 series of fabrics provides adequate shear stability for handling in an industrial environment, and of these the 2-2

basket weave gives best tear resistance. As is pointed out in the conclusions section, optimum tear resistance does not necessarily yield maximum breaking strength. In fact, the data show that significant gains in tongue tear strength often are achieved with less than optimum breaking strength.

Table 9 presents results of the first series tests. These are the fabrics of the selection plan shown in table 5 that were woven wiht 840 denier yarn. The fabric of this series with greatest tear strength was the 28x28, 2-2 basket weave which gave an average 218 lbs. $\pm$ 1.5% for warp and filling directed tear tests. The dimensional stability of this fabric was adequate for handling during testing, whereas the 18x18 and 22x22 plain weave fabrics (the plain weave is inherently more stable than the 2-2 basket) were very unstable and extremely difficult to handle without obvious weave distortions occurring.

The 28x28 plain weave gave an average breaking strength of 362 lbs $\pm$ 2% for warp and filling directions. Yet, this fabric had less than half the tongue tear strength of the similar fabric in a 2-2 basket weave mentioned above.

The average of warp and filling tensile strength for the plain weaves ranged from 275 lbs for the 18x18 construction (92% of the theoretical value for nylon of 9 grams/denier tenacity) to 362 lbs for the 28x28 construction (78% of the theoretical value). Following a reverse trend in magnitude, the average tongue tear strength of the plain weave samples ranged from 167 lbs for the 18x18 construction to 103 lbs for the 28x28 construction. The tongue tear and tensile

Table 9. Test Results of First Series Fabrics (840 Den. Yarn)

Test \ Fabric	18 x 18 Plain	22 x 22 Plain	24 x 24 Plain	24 x 24 2/2 Broken Twill	28 x 28 Plain	28 x 28 1-3 W. Rib	28 x 28 2-2 W. Rib	28 x 28 2-2 F. Rib
TENSILE STRENGTH lbs. - Warp	292	318	329	306	370	368	356	355
TENSILE STRENGTH lbs. - Filling	258	328	381	357	353	201	345	368
TONGUE TEAR STRENGTH lbs. - Warp	167	117	111	187	100	167	242	138
TONGUE TEAR STRENGTH lbs. - Filling	*	125	113	148	106	138	143	227
AIR PERMEABILITY, $ft^3/min./ft^2$	91.2	25.7	14.3	34.6	7.3	13.8	17.1	10.5
THICKNESS, INCHES	0.11	0.012	0.014	0.014	0.015	0.020	0.018	0.020
AREAL DENSITY, oz/yd^2	4.4	5.2	5.6	5.7	6.5	6.6	6.6	6.5

* Yarn Slippage at the Free Edge Could Not Be Prevented.

Table 9 (continued) Test Results of First Series

Test \ Fabric	28 x 28 1/3 Broken Twill	28 x 28 1/3 Reg. Twill	28 x 28 2/2 Broken Twill	28 x 28 2/2 Reg. Twill	28 x 28 2-2 Basket
TENSILE STRENGTH lbs. - Warp	379	367	378	374	355
TENSILE STRENGTH lbs. - Filling	371	357	339	344	350
TONGUE TEAR STRENGTH lbs. - Warp	160	165	153	156	215
TONGUE TEAR STRENGTH lbs. - Filling	159	159	141	162	221
AIR PERMEABILITY, $ft^3/min./ft^2$	38.3	76.7	25.9	45.6	25.7
THICKNESS, INCHES	0.018	0.017	0.018	0.015	0.016
AREAL DENSITY, oz/yd^2	6.4	6.5	6.5	6.4	6.5

strengths follow an inverse, non-linear relationship for the constructions examined.

The fabric areal densities showed as expected that density of yarns (ends and picks per inch) determines the fabric density. The values are generally 0.4 oz/yd^2 greater than the theoretical value found for straight 840 denier yarns due to weave crimp.

Fabric thickness of the plain weaves increased nearly linearly from 0.011 inches to 0.015 inches as end and pick count increased from 18x18 to 28x28. In the 28x28 group, the weaves which had unbalanced float lengths in the warp and filling directions, e.g., the rib weaves, were 20 - 30% thicker than the plain weave.

The air permeability tests were repeatable for a single fabric and are a measure of fabric openness. Relating other fabric properties to air permeability in general experience is a difficult matter, and the data show that only a vague nonlinear trend exists in which the magnitude of air permeability is proportional to tear strength. This test was included because the literature survey indicated that increased tear strength generally followed with increased fabric openness. The plain weave fabrics follow the trend mentioned above, while varying the weave at fixed end and pick count produced unpredictable results.

The data from the first series of fabrics was used to determine an optimum end and pick count for a second series of fabrics constructed with 1050 denier yarn. An effective density of yarns less than that of the 28x28 construction was determined to be unsuitable in terms of fabric dimensional stability.

To determine the equivalent density of yarns for a fabric of 1050 denier nylon, the cover factor for the 28x28, 840 denier fabric was found using the formula:

$$\text{COVER FACTOR} = (P + E) \times D,$$

where P = picks/inch, E = ends/inch, and D = yarn diameter in inches (here the square root of yarn denier which is directly related to yarn diameter was substituted for D). For equivalent cover factor,

$$\frac{(P + E)_{840} \times D_{840}}{(P + E)_{1050} \times D_{1050}} = 1.$$

Thus, $(P+E)_{1050} = (P+E)_{840} \times \sqrt{840 / 1050.}$ Given the selection of the 28x28 construction in 840 denier yarn, the 1050 denier yarn should have a 24x24 construction.

The results from tests of the second series of fabrics is shown in Table 10. These tests confirmed that the 2x2 basket weave has significantly higher tear strength than other weaves of the same or lesser float length. The average tear strength of this weave was 252 lbs $\pm$ 6%. Recently obtained data, discussed later in Section Three of this report, indicate that the 3x3 basket weave performs better than the 2x2 basket when coated. The data of Table 10 indicate that this is the case. A valid set of filling tear data was not obtained for this fabric due to edge pull-out, despite the use of Elvamid adhesive and contact adhesive with folded and pressed edges. Eastman 910 and epoxy cements were found unsatisfactory due to brittle failure of the cement.

Fabric permeability, thickness and density were found to be as expected from the 28x28 construction fabrics of the previous series. Tensile strength

Table 10. Test Results of Second Series Fabrics
(1050 denier, 24 x 24 density)

Test \ Fabric	Plain	1/3 Broken Twill	2/2 Reg. Twill	2-2 Basket	3-3 Basket
TENSILE STRENGTH lbs. - Warp	326	341	329	351	369
- Filling	350	362	317	401	407
TONGUE TEAR STRENGTH lbs. - Warp	110	157	147	266	272*
- Filling	115	166	158	237	172
AIR PERMEABILITY, $ft^3/min./ft^2$	7.46	77.1	60.3	118.1	123.8
THICKNESS, INCHES	0.016	0.018	0.016	0.017	0.018
AREAL DENSITY, oz/yd^2	6.8	6.6	6.7	6.7	7.1

* Sufficient Edge Adhesion Could not be Developed to Prevent Some edge pull-out of Yarns.

data exhibited greater variability than was found in the first series fabrics. The 2x2 basket weave fabric averaged 375 lbs $\pm$ 7% for warp and filling tests. The 3x3 basket weave averaged 388 lbs $\pm$ 5%.

The last series of fabrics investigated includes special constructions which were not considered at the initiation of the contracted work because no general industrial experience existed for these fabrics. While this is still true, research level experience with carry-over into commercial practice is growing for these fabrics. Table 11 presents results for these fabrics.

The 2-2 basket weave fabric with twisted filling exhibited 20% less strength in the filling tear test than in the warp tear test. Compared with the equivalent fabric containing no twisted yarn, the average tear strength is same 10% lower for the fabric with yarn twist.

The 24x24, plain weave fabric constructed with 1500 denier Kevlar yarn gave tear results roughly double that of the equivalent fabric made with 1050 denier nylon yarn. Breaking strength of the Kevlar fabric was some two to three times greater, as would be expected from the increased fiber strength of Kevlar. The abrasion resistance and knot strength of Kevlar yarns are lower on a relative basis than for regular nylon yarns (ref.: Table 3). The 20% lower tensile strength in the filling direction when compared with tensile strength in the warp direction indicates that some abrasion may have occured in the quill winding and picking operations which filling yarn must undergo during the fabric formation process.

Table 11. Test Results of Special Series Fabrics

Test \ Fabric	24 x 24 2-2 Basket 1050 Den. Nylon With Twisted Filling	Plain Kevlar 1500 Denier	24 x 24 2/2 Twill 1050 Den. Nylon with Kevlar on 1" Centers	24 x 24 2/2 Twill 1050 Den. Nylon with Kevlar on ½" centers	24 x 24 2/2 Twill From Table 10. (For Ref. Only
TENSILE STRENGTH lbs. - Warp	360	969	*	*	329
- Filling	375	785	*	*	317
TONGUE TEAR STRENGTH lbs. - Warp	246	240	178	189	147
- Filling	209	233	-	-	158
AIR PERMEABILITY, $ft^3/min./ft^2$	405.6	1.5	*	*	60.3
THICKNESS, INCHES	0.024	0.017	*	*	0.016
AREAL DENSITY, oz/yd^2	7.0	9.5	*	*	6.7

* Otherwise Normal Specimens of this Second Series Fabric Were Hand Stitched With 1500 Denier Kevlar Yarn.

The remaining two fabrics in Table 11 are the result of an attempt to produce energy barrier fabrics. The time and cost required to develop a technique for producing an energy barrier fabric of the weave type and weight needed were not within the scope of this program (the technology is well established for light-weight parachute fabrics). The samples were produced by hand stitching Kevlar yarns in the 2/2 twill fabric of Table 10, a construction of moderate tear resistance (147 lbs. avg.). The barrier yarn was evaluated in a warp tear test only, and showed 20% improvement in tear strength for the sample with Kevlar on 1" centers and 25% improvement for Kevlar on ½" centers. The appearance of tear load versus elongation is illustrated below in Figure 4.

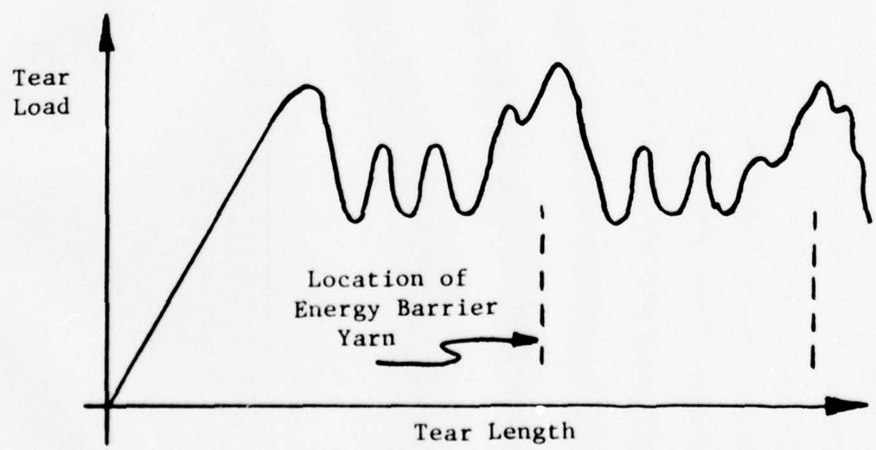


Figure 4. Illustration of Tear Curve

As this figure suggests, the advantage of an energy barrier type fabric is in having a blocking point for tear propagation. The traditional method of using a large bundle of yarns is unsuitable for use with a fabric coating process. However, use of a single, exceptionally strong yarn of Kevlar appears feasible.

Three triaxially woven fabrics were also tested, and these too represent an unusual type of fabric. Tongue tear strength of these fabrics was evaluated in three directions - perpendicular to the filling, parallel to the filling, and along a warp. For reference only, trapezoid tear tests* of these fabrics were conducted. Trapezoid tear is essentially a sequential single end tensile break test. Results of these tests appear in Table 12.

The tests show that the inverse relation of trapezoid tear strength to tongue tear strength follows previous discussion of tensile strength as it relates to tongue tear strength. The effect of weave design appears contractictory to results for biaxially woven fabric in that the average strength of the plain weave sample was greater than that of the basket weave sample.

No determination can be made at this time to explain the range of results obtained in tongue tear tests in the three directions. The range for plain triaxial fabric was 132 - 145 lbs; for basket triaxial fabric, 109 - 162 lbs; and for bi-plane triaxial, 117 - 142 lbs for the three test directions. As mentioned previously, these fabrics were constructed of different yarns than those used for the biaxially woven fabrics.

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* Federal Standard 191, Method 5136

Table 12. Test Results on Triaxial Fabrics

Test \ Fabric	18 x 18 x 18 Plain triaxial	9 x 9 x 9 Basket Triaxial	Bi-Plane Triaxial
TONGUE TEAR, lbs.			
- perpendicular to filling	145	162	125
- parallel to filling	139	109	142
- along warp	132	117	117
TRAPEZOID TEAR, lbs.			
- perpendicular to filling	91	264	204
- parallel to filling	110	438	369
- along warp	104	391	310
THICKNESS, inches	0.013	0.017	0.026
Area Density, oz./yd^2	6½	6½	13

THIRD SECTION: CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The following conclusions are based upon the results of observations and tests of the experimental fabrics.

1.) The effect of decreasing the number of warp ends and filling picks (end and pick count) is to decrease tensile strength, but increase tear strength. This agrees with cited literature which attributes improved tear strength to the yarn mobility of low end and pick density.

2.) A standard for tongue tear strength in excess of 200 lbs. can be established; but note that tensile strength as high as 400 lbs (ref.: MIL-T-52766) may not be achieved in optimum fabric design. Fabric tensile strength of 300 to 325 lbs was observed in these samples whose tear strength exceeded 200 lbs.

3.) At end and pick counts below 24x24 for fabrics made with 1050 denier nylon yarn and 28x28 for 840 denier yarn, the fabrics have very low dimensional stability, are thus very difficult to handle, and are of doubtful value as substrates for most commercial coating.

4.) A 2-2 basket weave gave the maximum tear strength of those fabrics tested, and is at an optimum of tear strength versus stability in the 24x24 construction using 1050 denier yarn. The 3-3 basket weave fabric is only marginally stable at 24x24 end and pick count. Thus, a denser, optimum fabric of this construction should not exhibit tear resistance significantly different from the 2-2 basket due to the detrimental effect of increased end and pick count on tear resistance.

(but note that after coating a 3-3 basket weave may perform better than a 2-2 basket weave - see the following section on translation of properties).

5.) Fabric weaves of the rib group and the 2/2 broken twill give unbalanced tear and tensile strengths for warp and filling directed tests. While having greater dimensional stability, these fabrics are weaker in tear than the 2-2 basket weave; thus are not recommended for the fuel tank program.

6.) The use of Kevlar yarn rather than tire cord quality nylon produces a stronger fabric both in breaking and tongue tear tests, based upon the comparison of plain weave fabrics of 24x24 construction.

7.) The use of 1050 denier nylon yarn rather than 840 denier yarn gives improved tear strength at equivalent cover factor.

8.) The triaxial weave fabrics tested showed less than 150 lbs tongue tear strength, but have the advantage of retaining integrity should yarns of one weave direction be severed. Improved triaxial fabric performance is needed before this structure could be recommended for the fuel tank program.

9.) Yarn twist at relatively low levels (2-3 turns per inch) has been cited as improving tear resistance for coated fabrics. The data for uncoated fabric with twisted filling shows a decrease in tear strength when the tear direction is across filling yarns, which should occur with the strength decrease caused by twist. Due to abrasion in the twisting operation, twisted Kevlar yarn may suffer significant less of breaking strength.

10.) The energy barrier concept, incorporated in this work by stitching a Kevlar yarn in an otherwise normal fabric sample, improved the tear strength. The differences in moduli of Kevlar and regular nylon and in boil shrinkage of the two fibers make the task of producing an energy barrier fabric difficult. The effect of modulus and boil shrinkage would be to cause buckling of the Kevlar component during weaving and during coating. Thus, this approach is not recommended for the fuel tank program until fabric production techniques are developed to successfully overcome these potential problems.

B. Factors Governing Properties of Coated Fabric

Research on improving tear resistance of skirts and seals for the Navy Surface Effect Vehicle (SEV) program can offer important guidelines for the fuel tank program. The SEV fabrics are much heavier (50-120 oz./yd^2) than those designed for a fuel tank. Flutter type fatigue and delamination are major problems with the SEV coated fabric. However, despite the fabric weight and end use environment differences, the trends established may be valid for the development of an improved fuel tank material. The following discussion is presented as a general survey of research on the SEV fabrics, where the substrate fabric and coating are treated as a single composite entity.

I.) General Construction Considerations

Skirts and seals are composite materials composed of woven fabric imbedded in a rubber matrix designed for shape retention, fatigue resistance, and strength. The fabric provides tensile and tear strength while being flexible. The rubber coating provides air impermeability, abrasion resistance, and impact

cushioning. Applied loads are transmitted to the substrate fabric through shear of the rubber matrix

An adhesive pre-coat is usually applied to the fabric and, while accounting for less than 1% of the total composite, has a prominent effect on skirt performance. The precoat prevents fluid wicking and improves the interfacial bond strength between rubber and fabric.

The design of composite materials used for skirts and seals reflects the need to achieve material properties not found in any of the components acting alone.

II.) Substrate Fabric

Traditional woven fabric consists of two sets of yarns, warp and filling, interlaced at right angles. In addition to this, two other classes of fabric are available. Triaxially woven fabric contains three sets of yarns, two warps and one filling, woven at 60° angles. Uniaxial fabric, an example of which is tire reinforcement fabric, is a warp sheet of yarns interlaced by a small filling yarn at relatively long intervals. To reinforce a skirt, two or more of the uniaxial fabrics would be laminated together at appropriate angles.

The strength of a woven fabric is determined by fiber strength, yarn construction, and fabric construction. Generally, increasing yarn twist or crimp due to interlacing decreases fabric strength. Reduced yarn crimp is achieved in weaves containing long floats, such as basket or twill weaves. Due to long floats, yarn mobility also increases, which in turn increases fabric tear strength and flexural compliance.

The fabrics studied in the SEV program were conventionally woven heavy fabrics of over 1000 lb. tensile and tear strengths and 60 oz/ yd^2 areal density. Maximum reinforcement (1000 lbs. tear) occurred in a 3 x 4 basket weave fabric using a yarn with moderate twist.

III.) Fabric Seams

Fabric seams are a region of discontinuity and a potential source of defects. The number of seams is decreased by increasing fabric width. Manufacturers of conventional industrial fabrics are limited by their equipment to a fabric width of 82 inches. However, Fourdrinier screens used in the paper industry are woven to widths of up to 40 feet. This potential source of wide fabric reinforcement for SEV skirt systems has not been investigated.

The method of applying the elastomer coating is restricted for wide fabrics since calendering machines are limited to 83 inch width. An available method is hand lay-up, vacuum bagging, and autoclave curing.

IV.) Adhesive Pre-Coating

Chemical adhesion of the fabric to the elastomeric coating compound gives the strongest bond. Primers are compounds which react with both the synthetic yarns of the substrate fabric and the rubber. Thorough penetration of the primer adhesive into fiber bundles increased bond strength and resistance to wicking, but also increases stiffness.

A base coat or tie coat may be used after application of the primer to improve processing characteristics and adhesion. The relative merits of applying the adhesive precoat to the yarn prior to weaving has not been investigated. This could improve adhesive

penetration and thereby enhance the rubber to filament bond. The yarn handling methods for applying the pre-coat are available in the textile industry.

V.) Elastomeric Coating

Little information is available in the literature on the manner in which the fabrics used for SEV skirts have been coated. However, indications are that calendering is used most frequently. Preliminary evaluation of vacuum bagging achieved less penetration of the elastomer into the fabric because of the lower pressure available to force flow into the interstitial spaces.

The surface of coated fabrics can be treated to give various effects. While very little information is available on the treatments for skirts and seals, examples of those available include gloss, coefficient of friction modified, abrasion resistant, and ultra-violet absorbent surfaces.

C. Recommendations

This survey abstract of SEV literature indicated that greatest success in the SEV program was obtained with a 3-4 basket weave construction using moderately twisted yarns. The experimental study, reported herein indicated that considering weavability of the much lighter weight fuel tank fabrics, a 2-2 basket weave fabric constructed with 24x24 end and pick count of 1050 denier Dupont Type 715 nylon yarn can achieve tear strength in excess of 200 lbs, while retaining adequate dimensional stability. Thus, the recommendation for a future standard based upon the thickness and density maxima imposed by MIL-T-52766 is that tear strength be doubled to a minimum of 200 lbs., but minimum breaking

strength be decreased from 400 lbs to 300 lbs (provided that analysis of tank skin loads proves the feasibility of using lower tensile load requirements). Since moderate yarn twist (2-3 turns per inch) is reported to improve coated fabric tear resistance and is compatible with tear and tensile strengths of 200 lbs. and 300 lbs., respectively, it is recommended that this also be considered in a future standard.

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Appendix A

Experimental Data

APPENDIX A
EXPERIMENTAL RESULTS

PART I. Data for Table 9: Fabrics Constructed with 840 Denier Yarn.

1.) 18 x 18 Plain Weave

TONGUE TEAR TEST (lbs.)

	Warp	**# 1:** 107, 140, 180, 225, 230	**avg.**	176
(avg. = 167)		**# 2:** 104, 139, 188, 176, 175	**avg.**	156
		# 3: 170, 167, 170, 170, 171	**avg.**	170
	Filling	**# 1:** severe slip	**avg.**	
(avg.)		**# 2:** 155, 151, 204, 210, 215	**avg.**	187
		# 3: severe slip	**avg.**	

TENSILE TEST (lbs.)

Warp	: 280, 272, 300, 298, 310	**avg.**	292
Filling	: 255, 256, 260, 250, 267	**avg.**	258

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 6 mm Data: 8.7, 6.2, 8.3 avg. 7.7

A.P. Value = 91.2

THICKNESS (inches): 0.011, 0.010, 0.011 **avg.** 0.011

2.) 22 x 22 Plain Weave

TONGUE TEAR TEST (lbs.)

	Warp # 1:	141, 127, 119, 125, 118	avg. 126
(avg. =117)	# 2:	117, 104, 115, 109, 101	avg. 109
	# 3:	139, 102, 127, 105, 101	avg. 115
	Filling # 1:	109, 120, 114, 109, 132	avg. 117
(avg. = 125)	# 2:	126, 106, 146, 135, 120	avg. 127
	# 3:	106, 142, 149, 132, 130	avg. 132

TENSILE TEST (lbs.)

Warp :	310, 323, 281, 340, 334	avg. 318
Filling :	334, 313, 340, 323, 328	avg. 328

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 4 mm Data: 4.8, 6.3, 5.9 avg. 5.7

A.P. Value = 25.7

THICKNESS (inches): 0.012, 0.012, 0.012 avg. 0.012

3.) 24 x 24 Plain Weave

TONGUE TEAR TEST (lbs.)

	Warp	**# 1:**	127, 130, 106, 105, 117	**avg.** 117
(avg.= 111)		**# 2:**	112, 137, 108, 94, 103	**avg.** 111
		# 3:	106, 98, 104, 124, 94	**avg.** 105
	Filling	**# 1:**	128, 107, 117, 118, 112	**avg.** 116
(avg.= 113)		**# 2:**	135, 124, 116, 117, 113	**avg.** 121
		# 3:	143, 121, 120, 108, 122	**avg.** 101

TENSILE TEST (lbs.)

Warp	:	320, 338, 314, 350, 325	**avg.** 329
Filling	:	380, 362, 420, 390, 355	**avg.** 381

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 3 mm Data: 4.9, 4.7, 6.6 avg. 5.4

A.P. Value = 14.3

THICKNESS (inches): 0.014, 0.014, 0.014 avg. 0.014

4.) 24 x 24 2/2 Broken Twill

TONGUE TEAR TEST (lbs.)

Warp	# 1:	250, 245, 265, 205, 200	avg. 233
(avg.= 187)	# 2:	186, 186, 153, 162, 147	avg. 167
	# 3:	160, 159, 159, 164, 160	avg. 160
Filling	# 1:	144, 155, 135, 133, 134	avg. 140
(avg.= 148)	# 2:	141, 147, 151, 137, 137	avg. 143
	# 3:	164, 164, 165, 148, 158	avg. 160

TENSILE TEST (lbs.)

Warp	: 302, 297, 297, 300, 337	avg. 306
Filling	: 380, 376, 383, 316, 333	avg. 357

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 4 mm Data: 9.8, 12.1, 9.7 avg. 10.5

A.P. Value = 34.6

THICKNESS (inches): 0.014, 0.014, 0.014 avg. 0.014

5.) 28 x 28 Plain

TONGUE TEAR TEST (lbs.)

	Warp	# 1: 110, 97, 98, 84, 105	**avg.** 99
(**avg.**= 100)		# 2: 98, 104, 98, 102, 102	**avg.** 101
		# 3: 110, 96, 107, 99, 91	**avg.** 101
	Filling	# 1: 109, 99, 92, 92, 94	**avg.** 97
(**avg.**=)		# 2: 111, 116, 122, 142, 122	**avg.** 123
		# 3: 110, 109, 96, 86, 90	**avg.** 98

TENSILE TEST (lbs.)

Warp	: 355, 365, 363, 410, 356	**avg.** 370
Filling	: 380, 335, 400, 330, 318	**avg.** 353

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 2 mm   Data: 7.3, 8.5, 7.5   **avg.** 7.8

A.P. Value = 7.3

THICKNESS (inches): 0.015, 0.015, 0.015   **avg.** 0.015

6.) 28 x 28 1-3 W. RIB

TONGUE TEAR TEST (lbs.)

	Warp	# 1:	158, 162, 183, 165. 161	avg. 166
(avg. = 167)		# 2:	168, 163, 167, 172, 166	avg. 166
		# 3:	164, 162, 178, 165, 177	avg. 169
	Filling	# 1:	152, 153, 134, 136, 138	avg. 143
(avg. = 138)		# 2:	128, 133, 121, 114, 124	avg. 124
		# 3:	150, 148, 153, 140, 142	avg. 147

TENSILE TEST (lbs.)

Warp	:	383, 370, 362, 395, 328	avg. 368
Filling	:	300, 315, 255, 310, 325	avg. 301

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 3 mm Data: 4.5, 4.4, 6.4 avg. 5.1

A.P. Value = 13.8

THICKNESS (inches): 0.020, 0.019, 0.020 avg. 0.020

7.) 28 x 28 2-2 W. RIB

TONGUE TEAR TEST (lbs.)

	Warp **#** 1:	249, 263, 269, 242, 230	**avg.** 251
(avg. = 242)	**#** 2:	261, 255, 236, 238, 238	**avg.** 246
	# 3:	265, 228, 231, 217, 208	**avg.** 230
	Filling **#** 1:	175, 157, 140, 140, 125	**avg.** 147
(avg. = 143)	**#** 2:	162, 137, 143, 131, 138	**avg.** 142
	# 3:	176, 129, 132, 133, 137	**avg.** 141

TENSILE TEST (lbs.)

Warp	: 325, 393, 375, 300, 385	**avg.** 356
Filling	: 317, 345, 372	**avg.** 345

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 3 mm Data: 8.7, 6.2, 8.3 avg. 7.7

A.P. Value = 17.1

THICKNESS (inches): 0.018, 0.017, 0.018 **avg.** 0.018

8.) 28 x 28 2-2 F. RIB

TONGUE TEAR TEST (lbs.)

	Warp	# 1:	128, 153, 119, 123, 117	avg. 128
(avg.= 138)		# 2:	173, 137, 130, 126, 125	avg. 138
		# 3:	178, 157, 139, 128, 140	avg. 148
	Filling	# 1:	210, 230, 202, 211, 235	avg. 218
(avg.= 227)		# 2:	305, 255, 245, 235, 224	avg. 253
		# 3:	215, 215, 222, 205, 197	avg. 197

TENSILE TEST (lbs.)

Warp	:	384, 325, 322, 388	avg. 355
Filling	:	390, 330, 382, 392, 345	avg. 368

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 2 mm Data: 17.1, 12.9, 17.3 avg. 15.8

A.P. Value = 10.5

THICKNESS (inches): 0.020, 0.019, 0.019 avg. 0.020

9.) 28 x 28 1/3 Broken Twill

TONGUE TEAR TEST (lbs.)

	Warp # 1:	200, 157, 165, 157, 153	avg.	166.4
(avg.= 160)	# 2:	177, 174, 160, 160, 165	avg.	167.2
	# 3:	160, 150, 146, 141, 140	avg.	147.4
	Filling # 1:	167, 158, 172, 158, 150	avg.	161.0
(avg.= 159)	# 2:	148, 149, 169, 164, 143	avg.	154.6
	# 3:	210, 158, 145, 153, 136	avg.	160.4

TENSILE TEST (lbs.)

Warp :	344, 378, 402, 380, 390	avg.	378.8
Filling :	393, 335, 342, 385, 398	avg.	370.6

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 4 mm Data: 14.4, 9.2, 13.4 avg. 12.3

A.P. Value = 38.3

THICKNESS (inches): 0.018, 0.018, 0.018 avg. 0.018

10.) 28 x 28 1/3 Reg. Twill

TONGUE TEAR TEST (lbs.)

	Warp # 1:	165, 170, 175, 173, 167	avg. 170
(avg.= 165)	# 2:	158, 157, 175, 174, 165	avg. 166
	# 3:	150, 165, 157, 167, 156	avg. 159
	Filling # 1:	192, 148, 148, 163, 159	avg. 162
(avg.= 159)	# 2:	161, 174, 157, 145, 146	avg. 157
	# 3:	164, 150, 159, 159, 157	avg. 158

TENSILE TEST (lbs.)

Warp :	385, 412, 368, 308, 360	avg. 367
Filling :	365, 368, 308, 370, 372	avg. 357

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 6 mm Data: 10.9, 8.9, 9.0 avg. 9.6

A.P. Value = 76.7

THICKNESS (inches): 0.017, 0.017, 0.017 avg. 0.017

11.) 28 x 28 2/2 Broken Twill

TONGUE TEAR TEST (lbs.)

	Warp # 1:	180, 157, 158, 167, 139	avg.	160
(avg. = 153)	# 2:	182, 142, 143, 149, 140	avg.	151
	# 3:	152, 144, 147, 146, 148	avg.	147
	Filling # 1:	163, 144, 145, 126, 131	avg.	142
(avg. = 141)	# 2:	157, 140, 132, 145, 130	avg.	141
	# 3:	157, 143, 140, 125, 128	avg.	139

TENSILE TEST (lbs.)

Warp :	345, 360, 380, 420, 385	avg.	378
Filling :	365, 345, 300, 358, 325	avg.	339

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 4 mm Data: 5.3, 6.5, 5.5 avg. 5.8

A.P. Value = 25.9

THICKNESS (inches): 0.017, 0.018, 0.018 avg. 0.018

12.) 28 x 28 2/2 Reg. Twill

TONGUE TEAR TEST (lbs.)

	Warp	# 1:	158, 166, 140, 142, 143	avg. 150
(avg.= 156)		# 2:	153, 155, 162, 155, 162	avg. 157
		# 3:	171, 162, 174, 164, 139	avg. 162
	Filling	# 1:	175, 165, 178, 153, 167	avg. 168
(avg.= 162)		# 2:	151, 181, 165, 140, 139	avg. 155
		# 3:	171, 157, 173, 159 154	avg. 163

TENSILE TEST (lbs.)

Warp	:	400, 377, 370, 336, 388	avg. 374
Filling	:	343, 310, 343, 390, 335	avg. 344

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 6 mm Data: 4.2, 3.7, 2.7 avg. 3.5

A.P. Value = 45.6

THICKNESS (inches): 0.014, 0.016, 0.015 avg. 0.015

13.) 28 x 28 2-2 Basket

TONGUE TEAR TEST (lbs.)

	Warp	# 1:	192, 210, 230, 235, 210	avg. 215
(avg.= 215)		# 2:	175, 175, 180, 195, 200	avg. 185
		# 3:	225, 223, 240, 255, 275	avg. 244
	Filling	# 1:	183, 212, 225, 250, 268	avg. 228
(avg.= 221)		# 2:	180, 195, 198, 222, 230	avg. 205
		# 3:	215, 225, 235, 235, 245	avg. 231

TENSILE TEST (lbs.)

Warp	:	365, 344, 370, 371, 323	avg. 355
Filling	:	352, 363, 345, 321, 366	avg. 350

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 4 mm Data: 6.1, 6.3, 4.8 avg. 5.7

A.P. Value = 25.7

THICKNESS (inches): 0.016, 0.016, 0.016 avg. 0.016

PART 2.) Test Data for Table 10.
(Fabrics with 1050 denier nylon yarn)

1.) 24 x 24 Plain Weave

TONGUE TEAR TEST (lbs.)

Warp	# 1:	110, 102, 115, 119, 118	avg. 113
(avg.= 110)	# 2:	112, 105, 104, 115, 145	avg. 116
	# 3:	98, 96, 110, 100, 98	avg. 100
Filling	# 1:	102, 106, 120, 102, 127	avg. 111
(avg.= 115)	# 2:	112, 113, 125, 118, 117	avg. 117
	# 3:	136, 119, 110, 105, 116	avg. 117

TENSILE TEST (lbs.)

Warp :	338, 300, 327, 327, 338	avg. 326
Filling :	302, 340, 387, 390, 332	avg. 350

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 2 mm Data: 5.8, 8.3, 10.2 avg. 8.1

A.P. Value = 7.46

THICKNESS (inches): 0.016, 0.015, 0.016 avg. 0.016

2.) 24 x 24 1/3 Broken Twill Weave

TONGUE TEAR TEST (lbs.)

	Warp	**# 1:**	149, 148, 150, 144, 150	**avg.** 148
(avg.= 157)		**# 2:**	150, 160, 155, 150, 150	**avg.** 153
		# 3:	180, 165, 170, 170, 160	**avg.** 169
	Filling	**# 1:**	206, 210, 205, 145, 135	**avg.** 180
(avg.= 166)		**# 2:**	160, 152, 150, 157, 149	**avg.** 154
		# 3:	148, 162, 177, 176, 156	**avg.** 164

TENSILE TEST (lbs.)

Warp	:	358, 342, 335, 355, 313	**avg.** 341
Filling	:	366, 375, 364, 350, 355	**avg.** 362

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 6 mm **Data:** 5.8, 9.7, 13.5 **avg.** 9.7

A.P. Value = 77.1

THICKNESS (inches): 0.018, 0.017, 0.018 **avg.** 0.018

3.) 24 x 24 2/2 Reg. Twill Weave

TONGUE TEAR TEST (lbs.)

Warp	# 1:	144, 134, 133, 140, 137	avg. 138
(avg.= 147)	# 2:	140, 142, 150, 148, 145	avg. 145
	# 3:	160, 162, 160, 162, 150	avg. 159
Filling	# 1:	175, 184, 150, 157, 155	avg. 164
(avg.= 158)	# 2:	157, 153, 160, 175, 164	avg. 162
	# 3:	153, 145, 138, 150, 150	avg. 147

TENSILE TEST (lbs.)

Warp	:	345, 305, 312, 327, 355	avg. 329
Filling	:	328, 250, 330, 346, 330	avg. 317

AIR PERMEABILITY ($ft.^3/min./ft.^2$)

Orifice Diam. = 6 mm Data: 5.8, 6.7, 5.5 avg. 6.0

A.P. Value = 60.3

THICKNESS (inches): 0.016, 0.017, 0.016 avg. 0.016

4.) 24 x 24 2-2 Basket Weave

TONGUE TEAR TEST (lbs.).

	Warp	# 1:	233, 238, 240, 275, 262,	avg. 252
(avg. = 266)		# 2:	304, 288, 282, 267	avg. 285
		# 3:	253, 252, 268, 285, 245	avg. 261
	Filling	# 1:	233, 230, 238, 238, 238	avg. 235
(avg. = 237)		# 2:	232, 227, 227, 213, 210	avg. 222
		# 3:	248, 260, 262, 255, 248	avg. 255

TENSILE TEST (lbs.)

Warp :	358, 345, 305, 377, 372	avg. 351
Filling :	407, 432, 413, 404, 350	avg. 401

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 8 mm Data: 11.1, 4.7, 4.8 avg. 6.9

A.P. Value = 118.1

THICKNESS (inches): 0.015, 0.018, 0.017 avg. 0.017

5.) 24 x 24 3-3 Basket Weave

TONGUE TEAR TEST (lbs.)

	Warp # 1:	265, 258, 255, 243, 220	avg.	248
(avg.= 272)	# 2:	Slip	avg.	
	# 3:	295, 300, 300, 298, 285	avg.	296
	Filling # 1:	155, 155, 158, 155, 175	avg.	160
(avg.= 172)	# 2:	200, 198, 185, 167, 150	avg.	180
(All test specimens gave yarn slip)	# 3:	183, 178, 175, 175, 177	avg.	178

TENSILE TEST (lbs.)

Warp :	315, 298, 398, 403, 430	avg.	369
Filling :	400, 348, 442, 410, 435	avg.	407

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 8 mm Data: 5.9, 6.6, 10.2 avg. 7.6

A.P. Value = 123.8

THICKNESS (inches): 0.017, 0.018, 0.019 avg. 0.018

Part 3.) Test Data for Table 11.
(Special Fabric Series)

1.) 24 x 24 2-2 Basket Weave (1050 denier nylon)
(with twisted filling yarn)

TONGUE TEAR TEST (lbs.)

	Warp	**# 1:**	235, 290, 270, 275, 285	**avg.** 271
(avg.= 246)		**# 2:**	240, 250, 245, 248, 250	**avg.** 247
		# 3:	210, 205, 215, 230, 242	**avg.** 220
	Filling	**# 1:**	190, 203, 200, 200, 195	**avg.** 198
(avg.= 209)		**# 2:**	213, 225, 230, 230, 215	**avg.** 223
		# 3:	203, 195, 220, 213, 195	**avg.** 205

TENSILE TEST (lbs.)

Warp	:	330, 368, 338, 394, 368	**avg.** 360
Filling	:	320, 355, 328, 453, 418	**avg.** 375

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 11 mm Data: 22.9, 21.6, 22.6 avg. 22.4

A.P. Value = 405.6

THICKNESS (inches): 0.024, 0.025, 0.024 avg. 0.024

2.) 24 x 24 Plain Weave (1500 denier kevlar)

TONGUE TEAR TEST (lbs.)

	Warp	# 1:	235, 230, 230, 240, 263	avg. 240
(avg.= 240)		# 2:	215, 210, 215, 225, 225	avg. 218
		# 3:	225, 248, 288, 240, 305	avg. 261
	Filling	# 1:	230, 230, 225, 243, 280	avg. 242
(avg.= 233)		# 2:	260, 235, 235, 210, 220	avg. 232
		# 3:	245, 220, 215, 230, 210	avg. 224

TENSILE TEST (lbs.)

Warp	:	870, 990, 965, 1050, Slip	avg. 969
Filling	:	755, Slip, Slip, 815, Slip	avg. 785

AIR PERMEABILITY (ft.^{3}/min./ft.^{2})

Orifice Diam. = 1 mm Data: 6.1, 7.8, 6.6 avg. 6.8

A.P. Value = 1.5

THICKNESS (inches): 0.017, 0.017, 0.017 avg. 0.017

Part 4. Test Data for Table 12.
(Triaxially Woven Fabrics)

1.) 18 x 18 x 18 Plain Weave

TONGUE TEAR (lbs.)

I.	Filling	:	134, 124, 142, 164, 162	avg. 145
II.	Filling	:	139, 142, 137, 141, 136	avg. 139
	Warp	:	145, 122, 125, 138	avg. 133

TRAPEZOIDAL TEAR (lbs.)

I.	Filling	:	91 (specimen slip)	avg. 91
II.	Filling	:	107, 116, 115, 102, 108	avg. 110
	Warp	:	99, 106, 105, 115, 92	avg. 104

THICKNESS (inches): 0.013, 0.013, 0.013 avg. 0.013

2.) 9 x 9 x 9 Basket Weave

TONGUE TEAR (lbs.)

I.	Filling	:	140, 172, 177, 160	avg. 162
II.	Filling	:	125, 104, 109, 102, 105	avg. 109
	Warp	:	122, 142, 112, 110, 99	avg. 117

TRQPEZOIDAL TEAR (lbs.)

I.	Filling	:	255, 234, 301, 295, 236	avg. 264
II.	Filling	:	419, 465, 394, 442, 469	avg. 438
	Warp	:	430, 420, 419, 322, 365	avg. 391

THICKNESS (inches): 0.017, 0.018, 0.017 avg. 0.017

3.) 37 x 37 x 27 B1 - Plane Weave

TONGUE TEAR (lbs.)

I.	Filling	:	113, 130, 122, 125, 132	avg.	125
II.	Filling	:	140, 142, 140, 137, 150	avg.	142
	Warp	:	107, 108, 119, 122, 131	avg.	117

TRAPEZOIDAL TEAR (lbs.)

I.	Filling	:	164, 199, 249, 204	avg.	204
II.	Filling	:	376, 460, 350, 298, 359	avg.	369
	Warp	:	311, 300, 310, 304, 325	avg.	310

THICKNESS (inches): 0.026, 0.026, 0.026 avg. 0.026

Appendix B

Development of a Multiaxial Tear Tester

Appendix B - Development of a Multiaxial Tear Tester

During this project, work was undertaken to develop a multiaxial tear tester in a fashion that would not hinder the principle thrust of the work. Following is a discussion of this work to date.

The purpose of the tester is to provide a means for evaluation of candidate fabrics for the fuel tank program in an environment more closely representative of field use conditions than the tongue tear test. Both slow tear propagation and rapid or spontaneous tear propagation are included in the design, determined by whether the specimen is mounted with a slit cut in the central region or cut under load by a pneumatically driven knife, respectively.

The principle for loading the fabric uniformly follows the well established ball burst or diaphram burst tests. A hydraulically pressurized, six inch diameter diaphram is mounted beneath the test specimen. Air pressure is used to supply the hydraulic pressure in a water filled reservoir. The reservoir serves to minimize the quantity of pressurized air, and hence minimize the stored energy of the system should the diaphram burst.

Figure B-1 is a schematic diagram of the tester. The main components are a pressure and flow rate regulated air supply, reservoir tank, liquid flow rate control, pressure chamber, diaphram, and fabric clamp ring, and Figure B-2 is a cross-sectional view of the specimen mounting arrangement. The flow rate regulator between the water filled tanks prevents sudden expansion of the compressed air in the reservoir should a diaphram failure

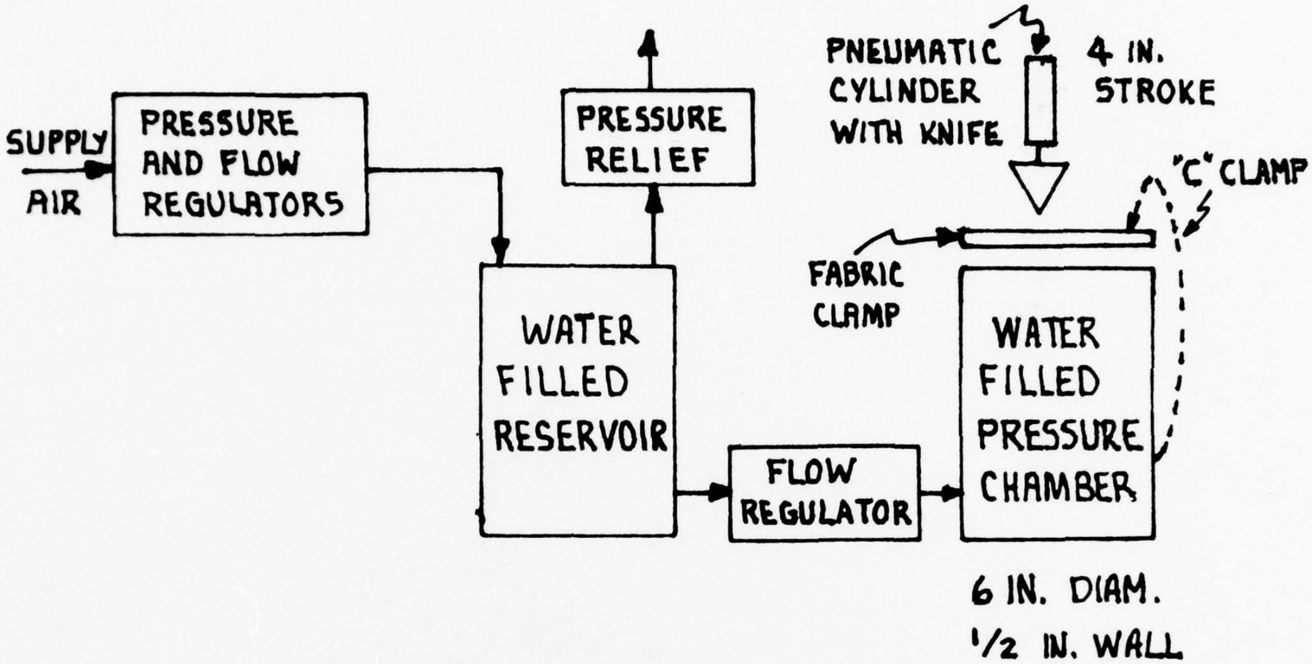

Figure B1 Schematic Diagram of Multiaxial Tester

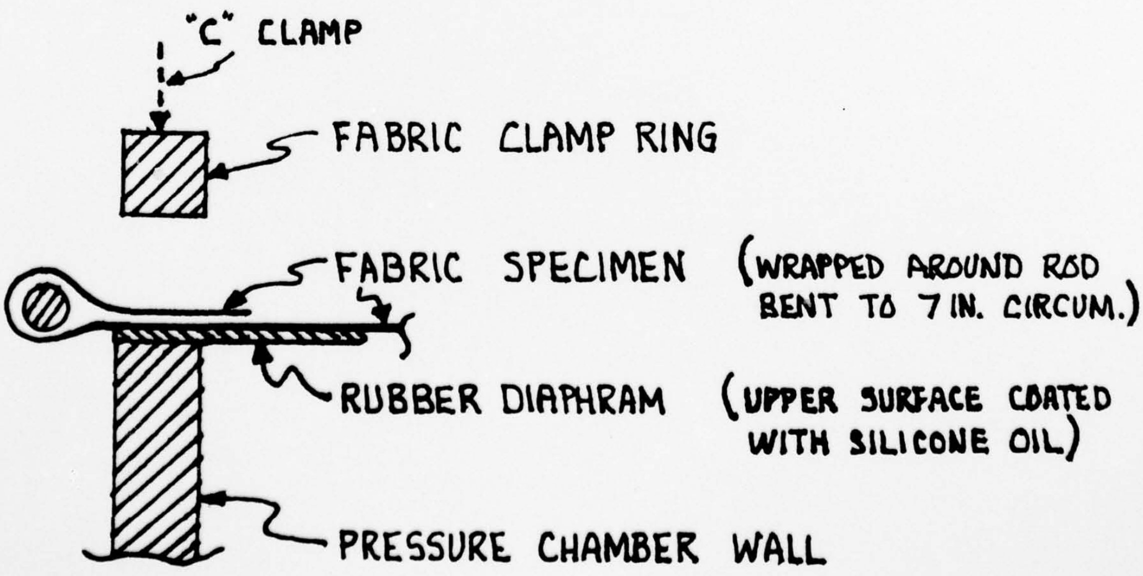

Figure B-2 Cross-Sectional View of Figure Clamp

occur. The pressure tanks are designed for 250 psi, but allowing a factor of safety of two, are used at pressures of 125 psi and below.

Problems that have been encountered to date include inadequacy of the seal above 80 psi at the diaphram-pressure chamber interface, and inability to achieve fabric slitting by the pneumatically driven knife prior to slitting and failure of the diaphram. The "O" ring seal is being replaced by a full width seal, and experiments with a flat edged knife are planned. Futher plans are in hand to produce a diaphram with a metal cup mounted in the center to achieve reasonable diaphram life.

Preliminary experimental results indicate that some effort will be needed to develop a reliable test method for this instrument. The first tests of 22 x 22 and 28 x 28 plain weave fabric made with 840 denier yarn incorporated a one inch slit in the fabric. The results for tear strength for the two fabrics were 52 psi and 48 psi, respectively. Both results had 4% coefficient of variation. Changing to a 1/2 inch pre-slit, the 28 x 28 plain weave fabric gave a burst strength of 66 psi (as opposed to 48 psi with a one inch pre-slit). Thus, tear results by the pre-slit method are quire sensitive to slit length, and require further work on a reliable test method.

Tests using the pneumatically driven knife with a pointed, double-edged blade showed that diaphram failure occurred prior to fabric failure. Due to the near instantaneous pressure drop inherent with hydraulic loading, no results were obtainable. Attempts to initiate failure with a flat, wedge edged blade were unsuccessful due to incomplete severing of the nylon filaments at the knife stroke length which produced a reasonably

small deflection of the diaphram.

Since both these test methods could be important to evaluation of coated fabrics, work will continue on this instrument in-house at Georgia Tech. Contact with Ft. Belvoir and the fuel tank program will be maintained as the work progresses.